MSFC -718 - ABSTRACT

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10/26/07

Metallic Hydrogen – Potentially A High Energy Rocket Propellant

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Pure metallic hydrogen is predicted to have a specific impulse (Isp) of 1700 seconds, but the reaction temperature is too high for current engine materials. Diluting metallic hydrogen with liquid hydrogen can reduce the reaction temperature to levels compatible with current material limits and still provide an Isp > 900 s. Metallic hydrogen has not yet been produced on earth, but experimental techniques exist that may change this situation. This paper will provide a brief description of metallic hydrogen and the status of experiments that may soon produce detectable quantities of this material in the lab. Also provided are some characteristics for diluted metallic hydrogen engines and launch vehicles.

MSFC-718-PRESENTATION

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Metallic Hydrogen - Potentially a High Energy Rocket Propellant

By

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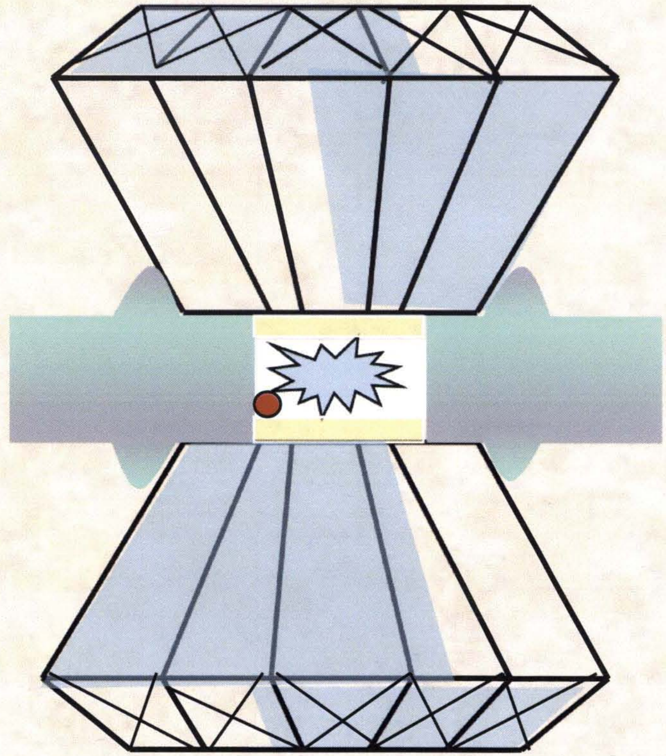

For

Tennessee Valley
Emerging Technology Conference

Huntsville, Alabama
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5-349422

Conceptual Launch Vehicles Using Metallic Hydrogen Propellant

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Contents:

Metallic Hydrogen as a Rocket Propellant

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Some Interesting Facts:

- **Recombining Hydrogen atoms release ~216 MJ/kg (ignoring pV energy);**

  compare to hydrogen/oxygen of Shuttle ~10 MJ/kg in main engines

- **Estimated density of metallic hydrogen 0.7 gm/cc**;

  compare to liquid hydrogen 0.07 gm/cc

Recent Calculations

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Isp=1700 s

J. W. Cole, I. F. Silvera, and J. P. Foote, "Conceptual Launch Vehicles Using Metallic Hydrogen Propellant," *STAIF 2008, accepted for publication,* 2007.

Isp=1400 s or greater

Pat Carrick, "Specific Impulse Calculations of High Energy Density Solid Cryogenic Rocket Propellants 1: Atoms in Solid H2," Phillips Laboratory PL-TR-93-3014, April 1993

Compare to liquid oxygen/molecular hydrogen
Isp= 454 s

A fuel with the specific impulse of metallic hydrogen would fundamentally change rocketry:

Can it be made in the Laboratory?

Will it be metastable?

What are possible engine and vehicle concepts?

The Wigner-Huntington Transition to Atomic Metallic Hydrogen (1935)

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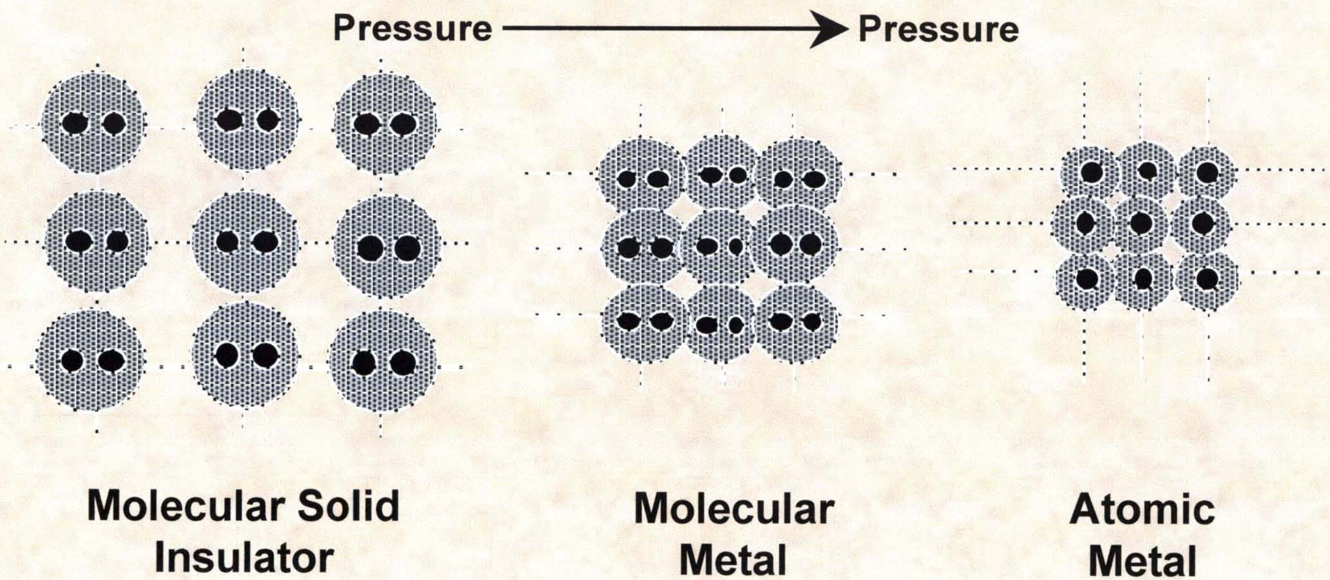
Predicted transition pressure:
250 Kbar (0.25 megabar or 25 Gigapascal (GPa)



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Important Historical Developments

- **Predicted Metal Insulator Transition in Solid Hydrogen**
  Wigner-Huntington, 1935
- **Predicted High Temperature Superconductivity in Metallic Hydrogen**
  Ashcroft, 1968
- **Metastability of metallic hydrogen, liquid at T=0 K**
  Russia (Kolos, Kagan), 1972
- **Structure of the Ground State at Ambient Pressure, Low T**
  Hardy, Silvera, McTague 1966-74
- **New Phases in the High Pressure Solid Hydrogens**
  ~1980-2005
  BSP Amsterdam 1981, Harvard 1990
  A-Phase (III) Geophys. Lab, Harvard, 1989-1990, 2005

Important Historical Developments (cont')

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- **Reverberating shock to conducting state in hot liquid hydrogen**
  Livermore, 1995

- **Equation of State**
  French-Geophys. Lab Collaboration,
  Harvard, 1982-1996

- **Experimental Melting line**
  French (Datchi, Loubeyre, LeToullec), 2000
  Gregoryanz et al, 2003

- **Highest Reported Pressures**
  342 GPa: Narayana, Luo, Orloff, and Ruoff, 1998
  320 GPa: Loubeyre,Occelli, and LeToullec, 2002

Hydrogen at High Pressure and Temperature

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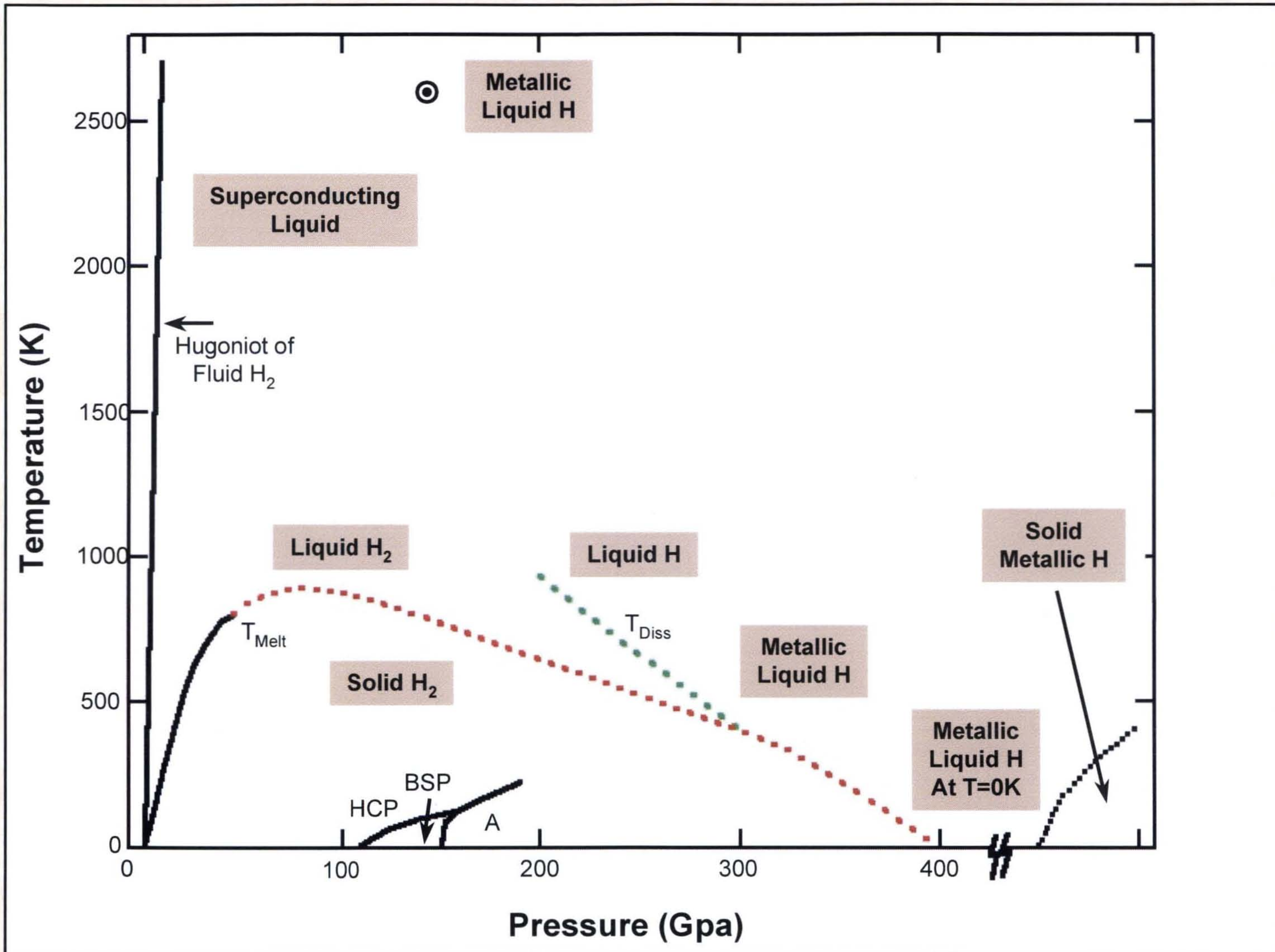

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Metastable States due to a Potential Barrier

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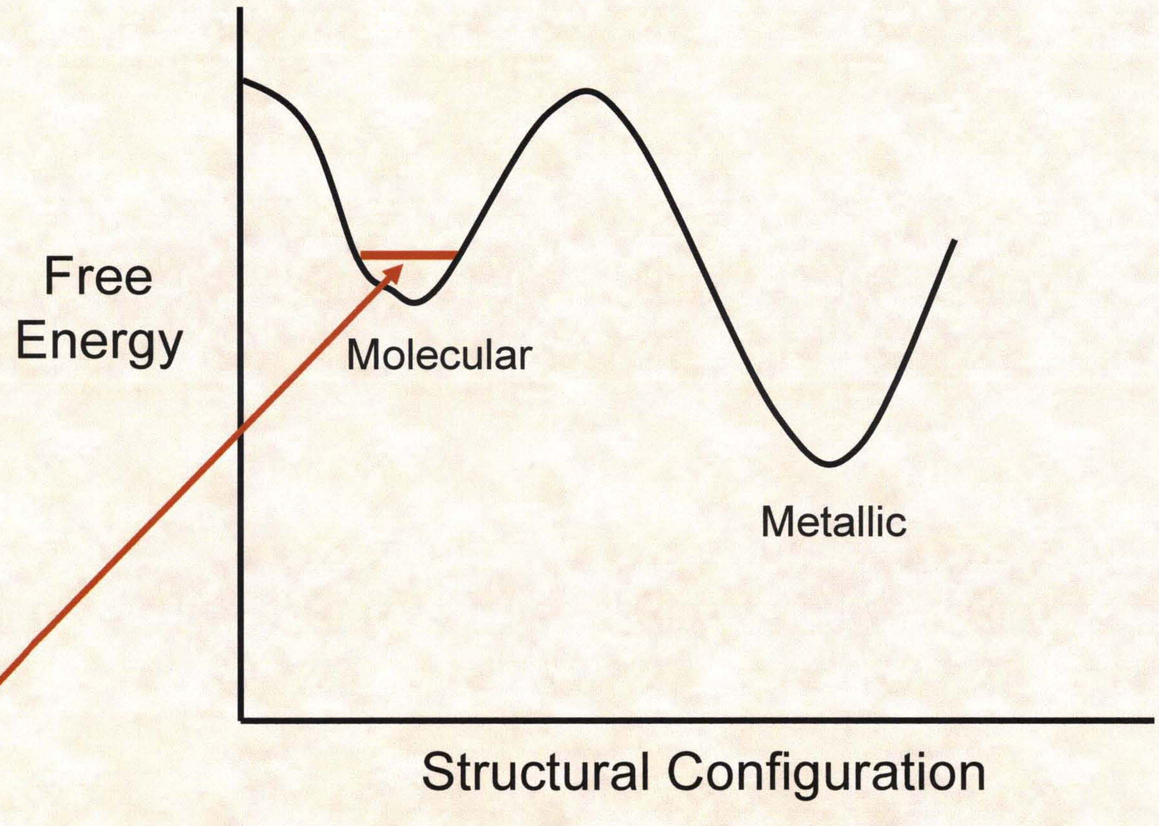
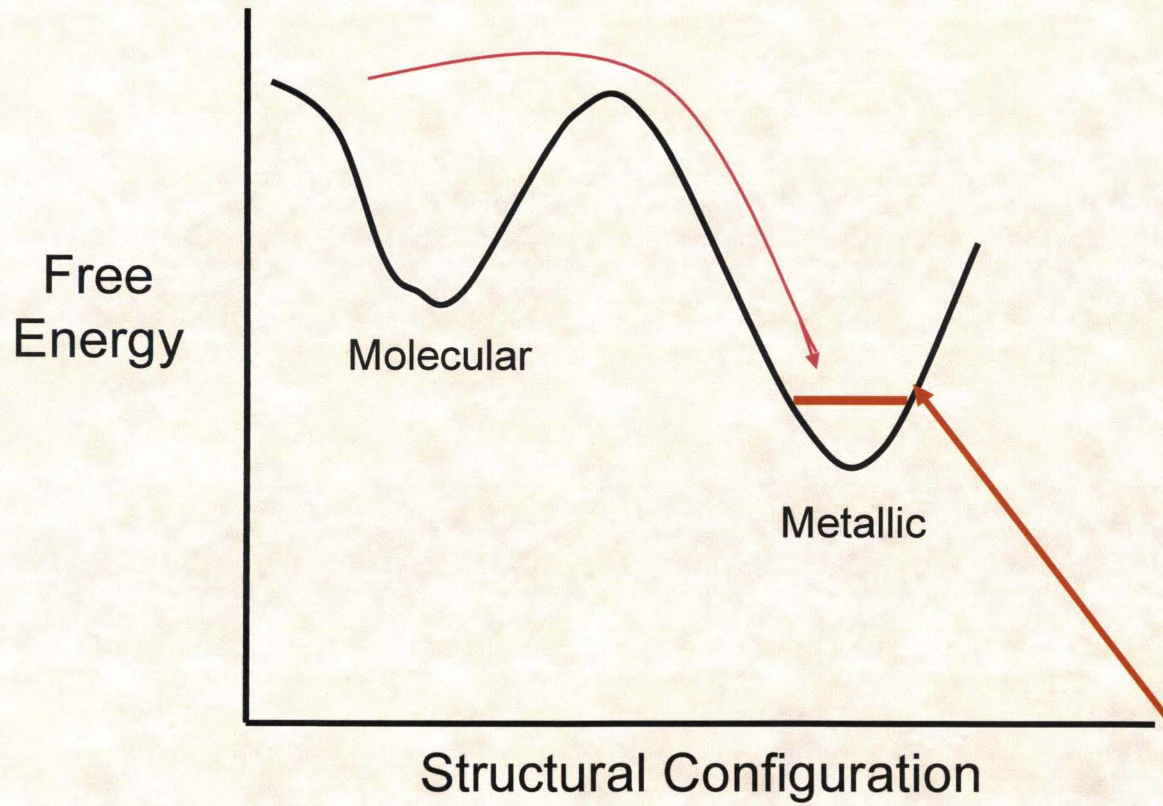


Low temperature:
Sample confined to molecular phase by barrier

Metastable States due to a Potential Barrier



High temperature:
Sample thermally activated to metallic phase

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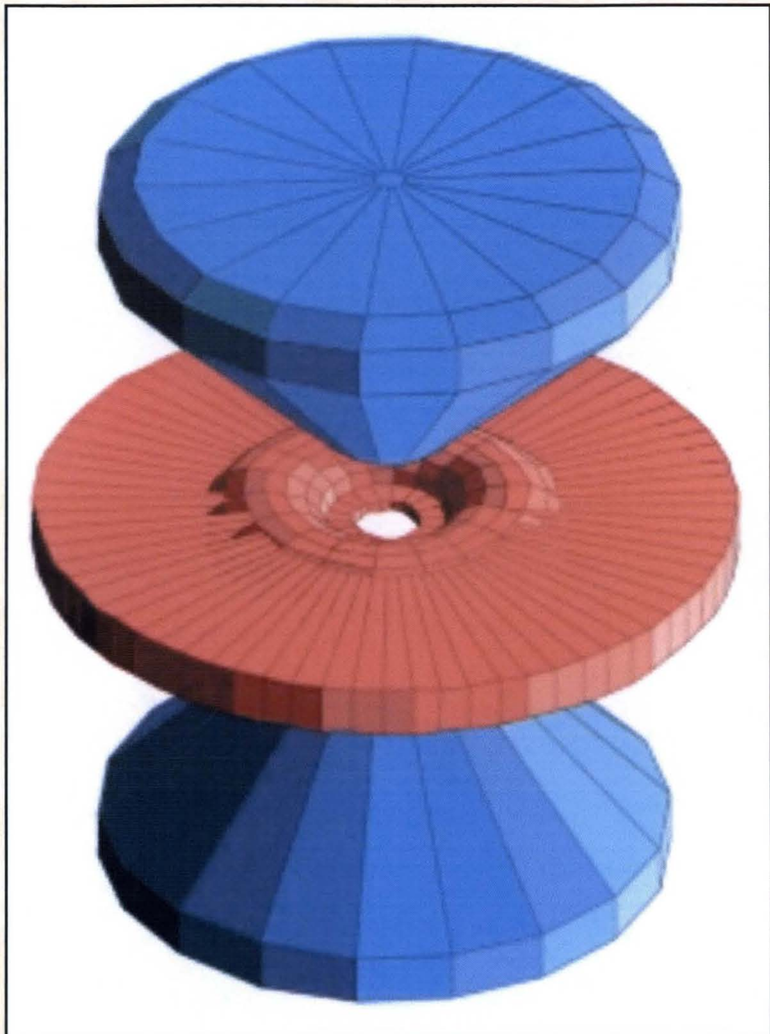
Diamonds and Gasket
(about 3-4 mm linear dimensions)



Diamond Anvil Cell
(about the size of a Coca-Cola bottle)

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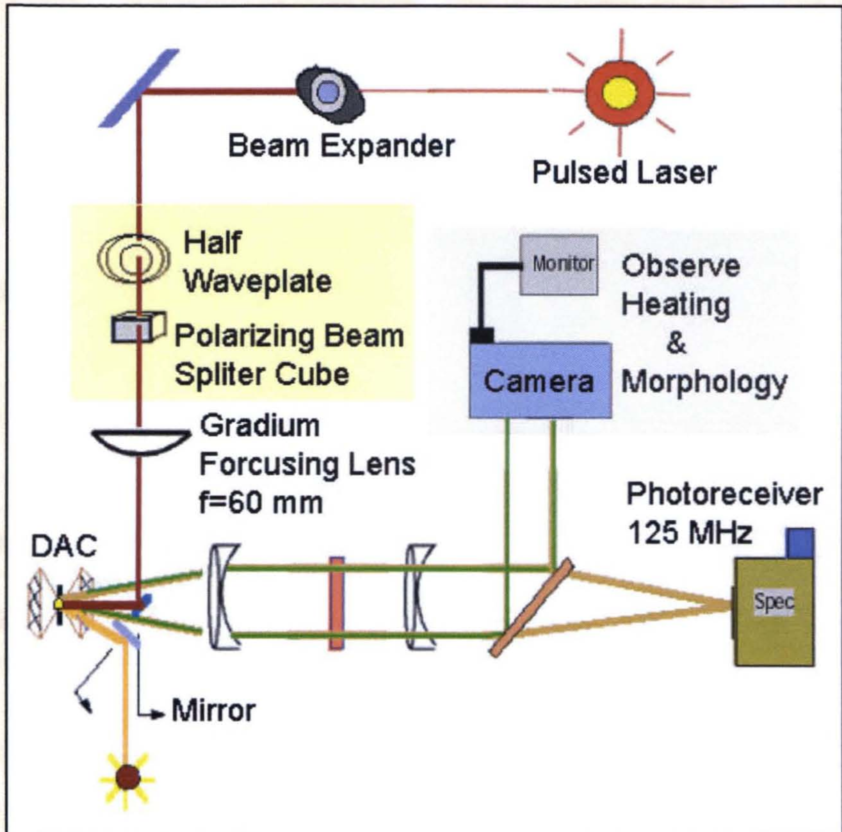
Diamond Anvil Cell (DAC) for Pursuit of Metallic Hydrogen



F. Silvera
Harvard University

Diamond Anvil Cell, Silvera

Gifford-McMahon Cryocooler cryostat and mounted DAC

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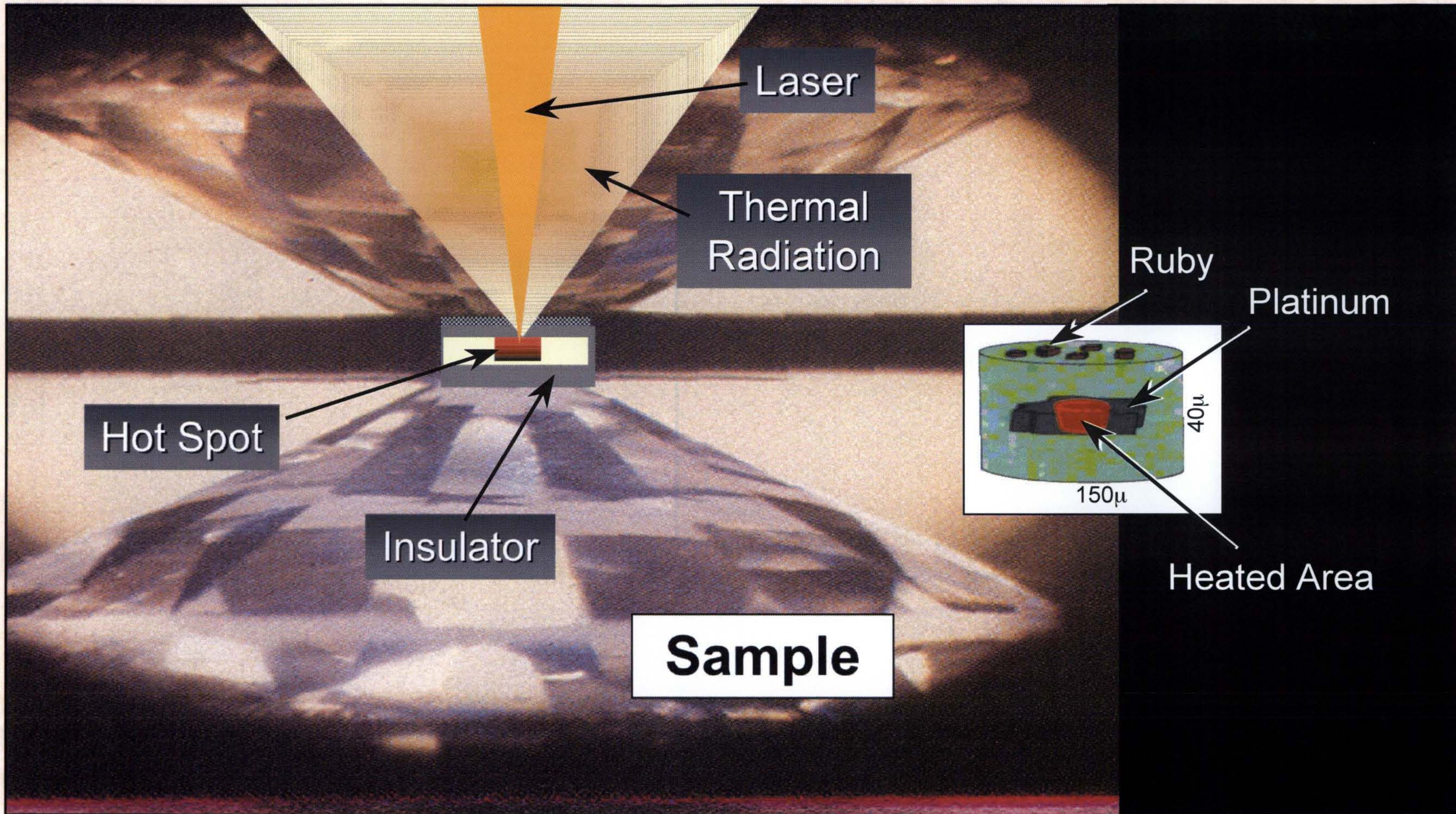
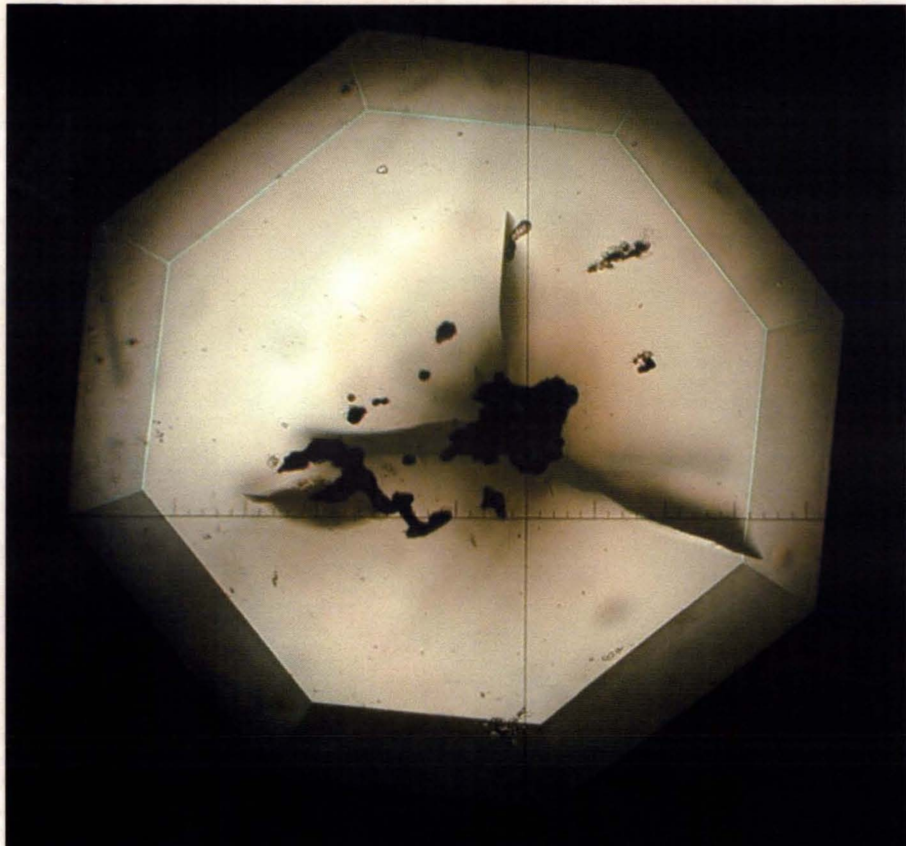
Laser Heated Sample in Diamond Anvil Cell



Sample can be heated to several thousand Kelvin

Examples of Graphitization of the Diamond Anvils from Pulsed Laser Heating.



Laser Heating of Hydrogen Challenges

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- Above about 500 K hydrogen diffuses into the confining gasket, and the sample is lost.
- Hydrogen diffuses into the diamonds, embrittles them, and they fail.

Solution to the Problem

Use pulsed rather than CW laser heating.
For a 100 nanosecond pulse there is adequate time for thermal equilibrium but not enough time for diffusion of hydrogen.

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Metallic Hydrogen – Summary

- Under pressures exceeding **4.5 Mbar**, the molecules on the lattice sites of insulating molecular hydrogen are **predicted to dissociate and transform into an atomic crystal.**
- This crystal is metallic (conductive) and **predicted to be metastable**, i.e., there is a large energy barrier that prevents it from transforming back to the molecular phase when the pressure is released to ambient conditions
- Above some **as yet unknown critical temperature** and possibly below some critical pressure, the atomic crystal loses its metastability and **the atoms recombine**, releasing the recombination energy.
- Just as diamond is a metastable form of carbon and requires heat to produce it synthetically, it may be that the same barrier that is responsible for the predicted metastability of mH prevents molecular hydrogen from transforming to the atomic phase at modest temperatures.
- **Diamond anvil and pulsed laser techniques** have been developed to enable heating of high-pressure hydrogen to possibly trigger the transition
- **Experiment may soon reveal these critical parameters** and other characteristics that will determine if metallic hydrogen can be useful for propulsion and other applications.

Recent Experimental Accomplishments, 2008

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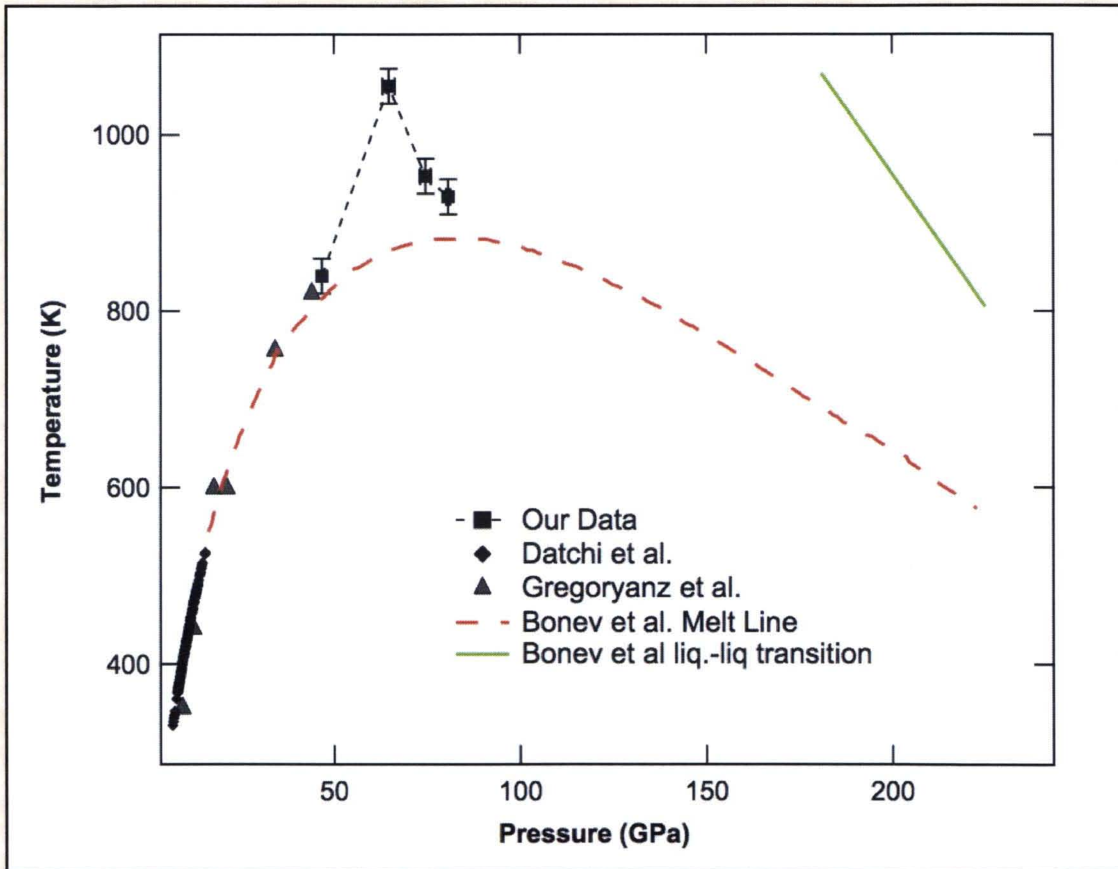
The Melting Line of Hydrogen at High Pressures

Shanti Deemyad and Isaac F. Silvera
Lyman Laboratory of Physics, Harvard University, Cambridge MA,02138

We have measured the melting line of molecular hydrogen as a function of pressure. Previous measurements have used ohmic heating of a diamond anvil cell and have been limited in pressure and temperature by diffusion of hydrogen into the gasket or diamonds. We use an innovative technique of pulsed laser heating. In this method the sample is hot sufficiently long to be in local thermodynamic equilibrium, but far too short of a time for diffusion of hydrogen into the components to limit the measurements. We find a peak in the melting line at P= 64.7 ± 4GPa and T=1055 ± 20 K.



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Engine Assumptions

Since the actual characteristics of metallic hydrogen are unknown, some assumptions must be made. Assume that metallic hydrogen:

- Is **stable** at reasonable temperatures and pressures.
- Has a high mass **density** (0.7 gm/cc).
- Can be **safely produced** and stored in large quantities for reasonable amounts of time at reasonable costs.
- **Sensitivities** to vibration, adiabatic compression (such as being squeezed in valve seals or pumps), and launch vehicle shock environments can be handled.
- Can be pressurized and pumped from a tank into a reaction chamber.
- **Recombination energy is available** consistent with equilibrium calculations.
- Energy **losses** due to engineering compromises are negligible.

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Engine Concept

- **Chemical Equilibrium Calculations** indicate that a reaction chamber filled with atomic hydrogen at 100 atm of pressure
  - will reach recombination/dissociation equilibrium at a **chamber temperature of > 5600 K** (> 9600 °F)
  - where »20% of the atomic hydrogen mass remains dissociated.
  - This would provide a **theoretical specific impulse of 1700 sec**
  - Clearly, the temperature is higher than any known chamber material can withstand. **Too Hot!**
- Our **Engine Concept** to reduce the chamber temperature is:
  - to **dilute** the metallic atomic hydrogen (mH) with cryogenic molecular Liquid Hydrogen (LH2)
  - at a low chamber pressure, and
  - to use regenerative and film cooling similar to the Space Shuttle main engines (SSMEs).

Liquid Hydrogen / Metallic Hydrogen

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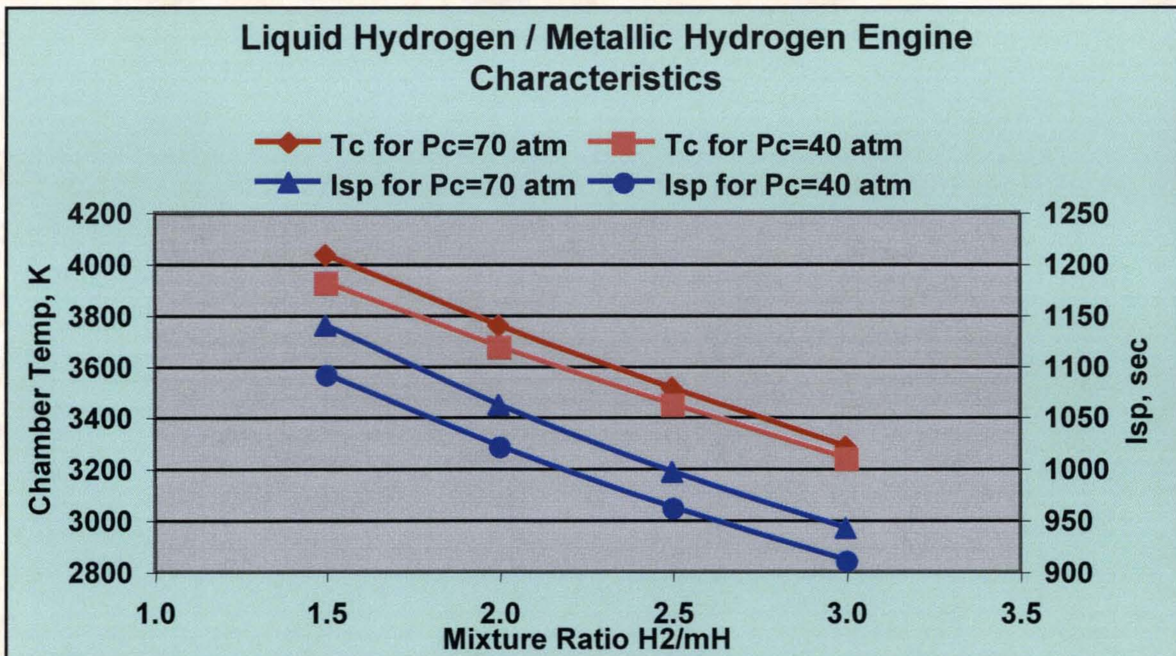
At 40 atm chamber pressure, using Chemical Equilibrium Calculations

- A mixture ratio of 3 indicates the chamber temperature is cooler than the SSME.
- A mixture ratio of 1.5 indicates the chamber temperature is ~4000 K, just beyond the current material limits of new materials such as hafnium carbide.
- The Isp range here is from 910 to 1090 s, and this implies single stage to orbit capabilities for a launch vehicle.



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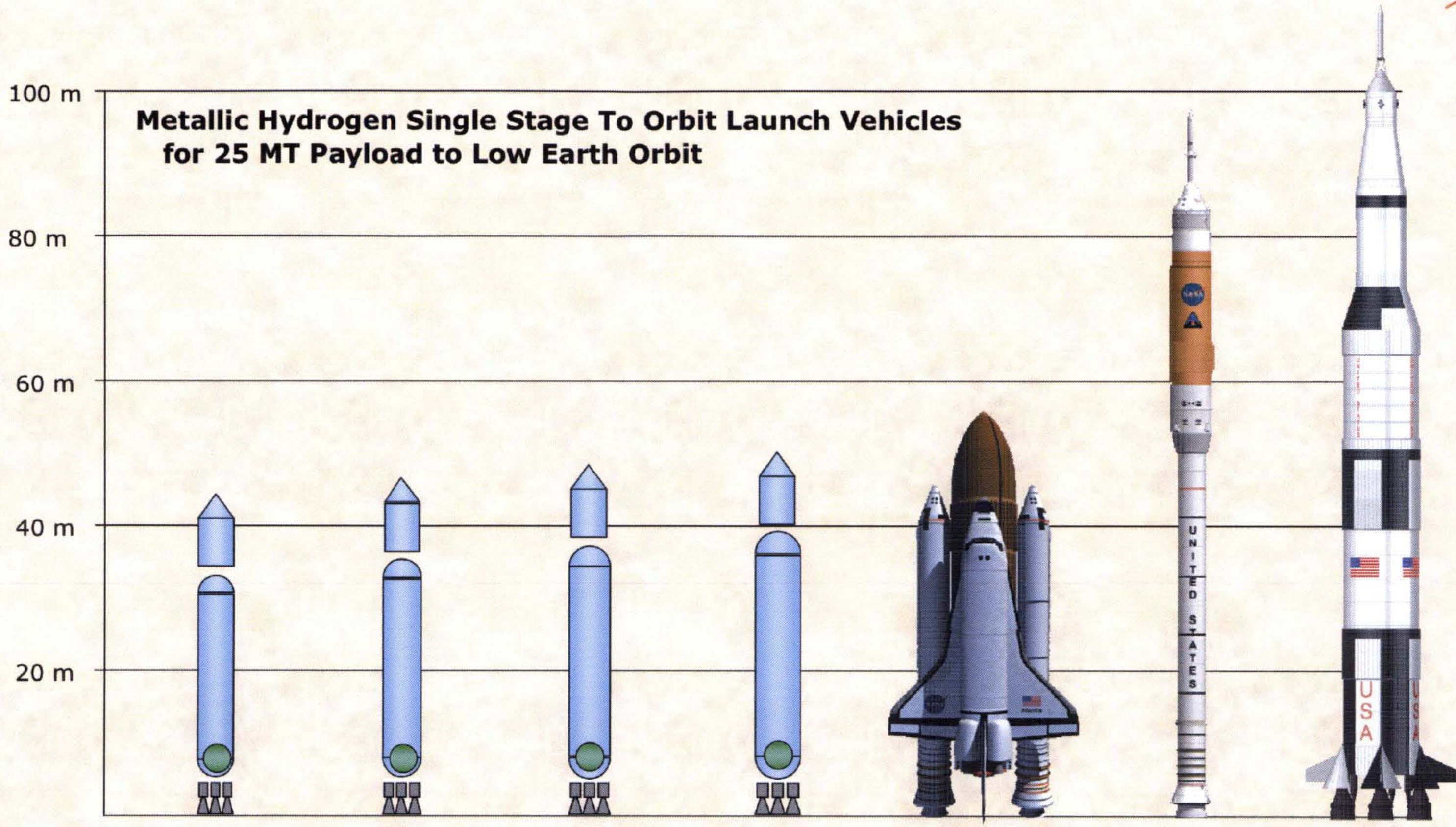
mH Vehicle Concepts

Hydrogen Cooled mH Launch Vehicles

- Expendable single-stage-to-orbit (SSTO)
- Launched vertically from a launch pad
- Delivering a 25 metric ton (MT) payload to Low Earth Orbit (LEO).
- The vehicle consists principally of
  - a large cryogenic hydrogen tank with a shrouded payload container above it
  - The metallic hydrogen is contained in a high-pressure spherical tank that is placed inside the cryogenic hydrogen tank to maintain a low temperature and some reasonable pressure.

Metallic Hydrogen Single Stage To Orbit Launch Vehicles for 25 MT Payload to Low Earth Orbit



Mix Ratio, H2/mH	1.5	2.0	2.5	3.0	Shuttle	Ares I	Saturn V
Height, m	44 m	46 m	48 m	50 m	56 m	98 m	111 m
Payload, MT	25 MT	25 MT	25 MT	25 MT	25 MT	22 MT	119 MT
Mass to LEO	39 MT	40 MT	42 MT	43 MT	130 MT w ET		
GLOW, MT	95 MT	104 MT	115 MT	126 MT	2000 MT	907 MT	2950 MT
Pld/GLOW Ratio	26.32%	23.98%	21.83%	19.89%	1.25%	2.40%	4.03%
Mass of mH, MT	22.4 MT	21.3 MT	20.8 MT	20.6 MT			
Chamb Temp, K	3925 K	3673 K	3448 K	3240 K			
Isp, sec	1091 s	1022 s	962 s	911 s	267-455 s*	267-426 s*	264-425 s*

* Stage Dependent

J. W. Cole, I. F. Silvera, and J. P. Foote, "Conceptual Launch Vehicles Using Metallic Hydrogen Propellant," *STAIF 2008, accepted for publication,* 2007.

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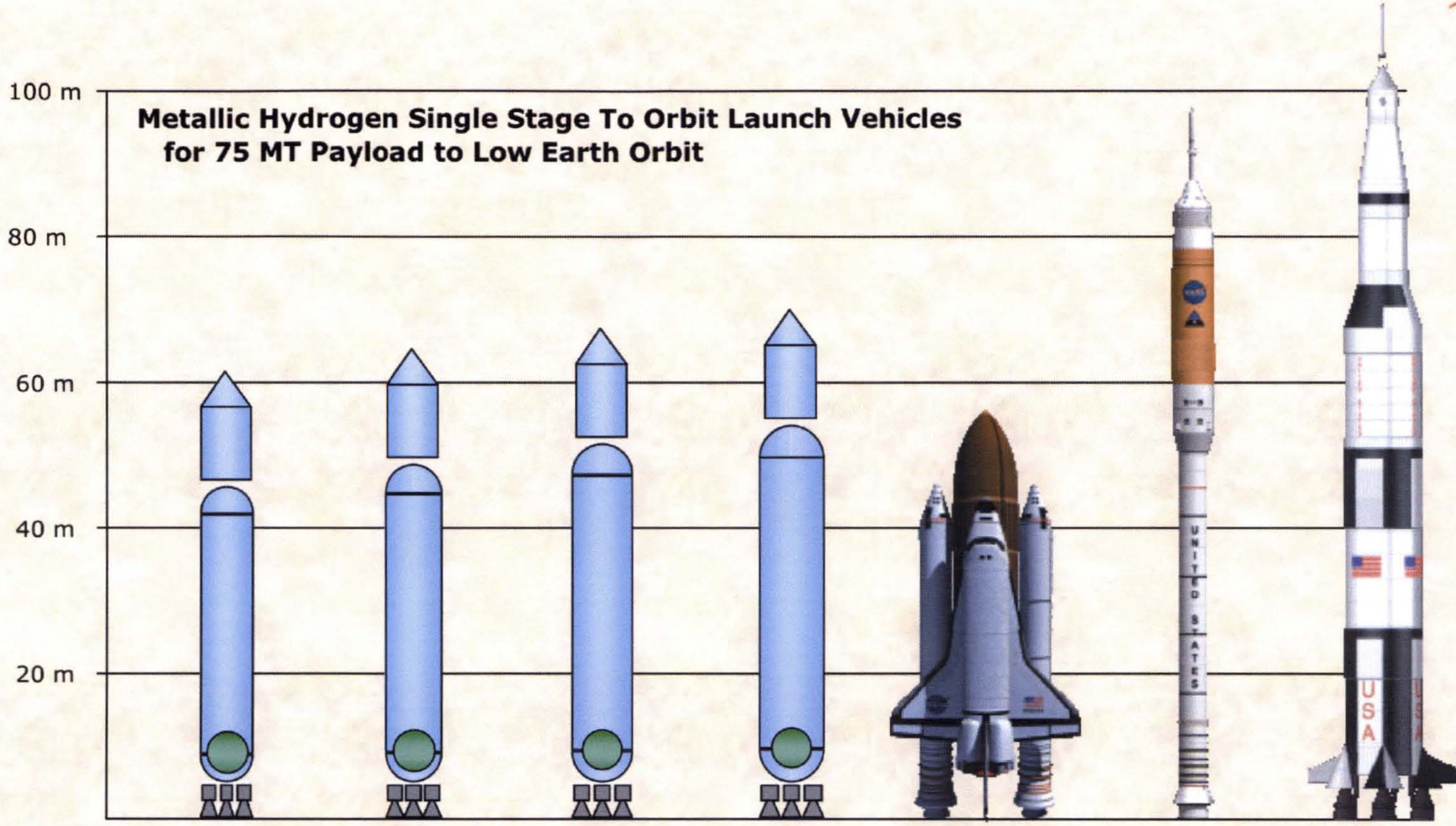
Metallic Hydrogen Single Stage To Orbit Launch Vehicles for 75 MT Payload to Low Earth Orbit



Mix Ratio, H2/mH	1.5	2.0	2.5	3.0	Shuttle	Ares I	Saturn V
Height, m	61 m	64 m	67 m	70 m	56 m	98 m	111 m
Payload, MT	75 MT	75 MT	75 MT	75 MT	25 MT	22 MT	119 MT
Mass to LEO	117 MT	121 MT	125 MT	130 MT	130 MT w ET		
GLOW, MT	285 MT	313 MT	344 MT	377 MT	2000 MT	907 MT	2950 MT
Pld/GLOW Ratio	26.32%	23.98%	21.83%	19.89%	1.25%	2.40%	4.03%
Mass of mH, MT	67.1 MT	63.9 MT	62.3 MT	61.7 MT			
Chamb Temp, K	3925 K	3673 K	3448 K	3240 K			
Isp, sec	1091 s	1022 s	962 s	911 s	267-455 s*	267-426 s*	264-425 s*

* Stage Dependent

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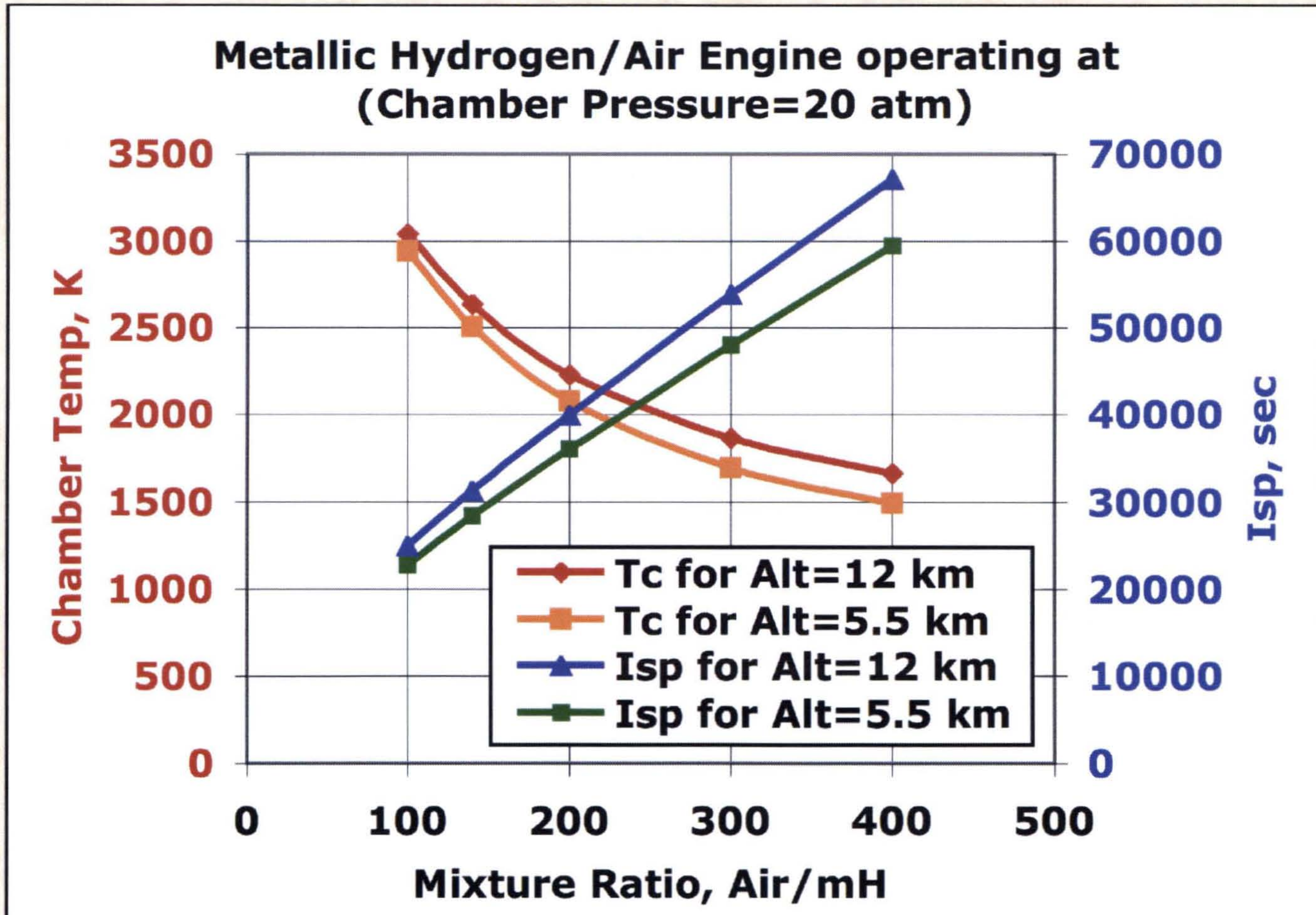
Air Cooled Metallic Hydrogen Engine

Alt (km)	Press (atm)	Pc/Pexit	Compressed Air T(K)	Chamber Press (atm)
5.5	0.5	40	800	20
12	0.2	100	1000	20



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Conclusions

- **Metallic hydrogen has not yet been produced** on Earth, but researchers may soon achieve this goal and determine its characteristics.
- If it proves to be usable as a rocket propellant with the anticipated specific energy, then engines and launch **vehicles can be designed** to use this propellant.
- The high specific energy creates chamber **temperatures too high** for currently available engine materials but **diluting the propellant can reduce** the chamber temperature.
- Liquid hydrogen diluent provides **impressive mass reductions** for a given payload size.
  - However, the **large size of the cryogenic hydrogen tanks** visually overwhelms the **advantages** of
    - the small size of the metallic hydrogen tank,
    - the fact that the GLOW is only »**25% that of historical vehicles**
    - payload delivery is accomplished as an **SSTO**.
- **Air Breathing Engines also look promising.**